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Microresonator isolators and circulators based on the intrinsic nonreciprocity of the Kerr effect

LEONARDO DEL BINO,^{1,2,†} JONATHAN M. SILVER,^{1,†} MICHAEL T. M. WOODLEY,^{1,2} SARAH L. STEBBINGS,¹ XIN ZHAO,^{1,3} AND PASCAL DEL'HAYE^{1,*}

¹National Physical Laboratory (NPL), Teddington TW11 0LW, UK

²Heriot-Watt University, Edinburgh, EH14 4AS Scotland, UK

³School of Electronic and Information Engineering, Beihang University, Beijing 100083, China

*Corresponding author: pascal.delhaye@npl.co.uk

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Nonreciprocal light propagation is important in many applications, ranging from optical telecommunications to integrated photonics. A simple way to achieve optical nonreciprocity is to use the nonlinear interaction between counterpropagating light in a Kerr medium. Within a ring resonator, this leads to spontaneous symmetry breaking, resulting in light of a given frequency circulating in one direction, but not in both directions simultaneously. In this work, we demonstrate that this effect can be used to realize optical isolators and circulators based on a single ultra-high- Q microresonator. We obtain isolation of >24 dB and develop a theoretical model for the power scaling of the attainable nonreciprocity. © 2018 Optical Society of America under the terms of the [OSA Open Access Publishing Agreement](#)

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1. INTRODUCTION

Nonreciprocal light propagation [1] is expected to play an important role in future photonic networks and optical data processing. A challenge for integrated photonic circuits is the realization of nonreciprocal elements like isolators and circulators [2]. Most optical isolators and circulators are based on the magneto-optic Faraday effect, which requires the integration of (electro)magnets [3–7]. Additional and compelling ways to achieve optical nonreciprocity include specially designed waveguides [8,9], optomechanical systems [10–14], parity-time symmetry breaking in resonator systems [15,16], indirect interband photonic transitions [17,18], and Brillouin scattering [19,20]. Other systems include spatially asymmetric “optical diodes” based on microresonator systems [21]. This device works based on asymmetric thermal resonance frequency shifts, with the disadvantage that it would suffer from dynamically reciprocal backward transmission in the spectral vicinity of the forward-transmitted light [22].

In this work we demonstrate a novel and simple isolator and circulator based on the intrinsic nonreciprocity of the Kerr nonlinearity in a single whispering gallery microresonator. The underlying Kerr-nonreciprocity corresponds to the physical effect that counterpropagating light induces twice the Kerr shift compared to the same amount of co-propagating light [23,24]. In a passive microresonator this leads to spontaneous symmetry-breaking between clockwise (cw) and counterclockwise (ccw) modes, which has been recently demonstrated [25,26]. Here, we make

use of this Kerr-nonlinearity-induced nonreciprocity in a microresonator in an add-drop configuration to realize a novel type of optical isolator and circulator [27]. In contrast to the case of spontaneous symmetry breaking, we intentionally set a microresonator into a state where it can only support the unidirectional propagation of light at a given frequency. Our measurements of the power scaling of the isolation are in excellent agreement with theoretical calculations based on the interplay of the Kerr nonlinearity with the modes of an ultra-high- Q microresonator.

Sending equal amounts of light in counterpropagating directions into a passive microresonator with $\chi^{(3)}$ nonlinearity leads to spontaneous symmetry breaking of the cw and ccw modes [25,26]. In addition, this effect induces optical nonreciprocity such that the cw and ccw modes of a microresonator acquire different resonance frequencies, as shown in Fig. 1(a).

In the biased state (with the input laser on) the coupled resonator breaks Lorentz reciprocity, and consequently light at the input frequency can only circulate in one direction. Only backward-propagating light (or noise) that falls within the spectrally well-separated cw resonance could get back to the input port (obeying dynamic reciprocity [22]). If desired, this narrow backward-transmitting window can be closed by using a second isolator with a slightly different mode splitting in series. Once the resonator is in a symmetry-broken state with unidirectional light propagation, the power sent in the backward direction toward the resonator can even exceed the forward-propagating power without changing the state of the resonator [26].

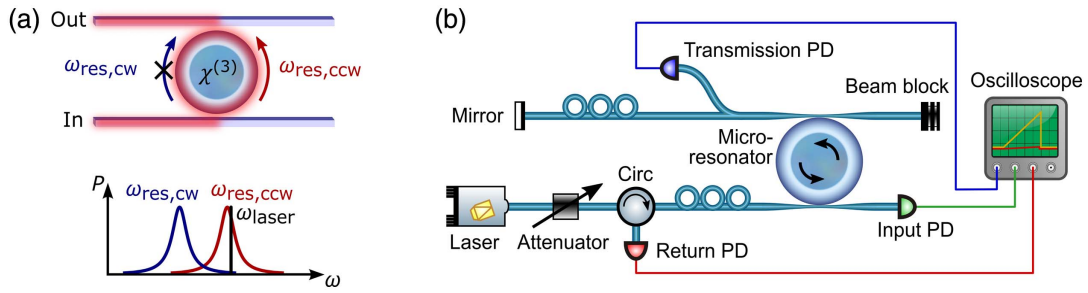


Fig. 1. Kerr nonreciprocity in a microresonator and the experimental setup for an isolator. (a) Schematic of the nonreciprocity. Light is coupled in the ccw direction through an ultra-high- Q microresonator in an add-drop configuration. The presence of the ccw light induces a Kerr shift that is twice as strong for cw circulating light, which leads to a resonance frequency splitting (shown in the lower panel). Consequently, backward-propagating light (cw) cannot pass through the resonator. (b) The experimental setup for the characterization of an isolator based on the Kerr nonreciprocity. Laser light is coupled through an ultra-high- Q silica microrod resonator using two tapered optical fibers. A fiber mirror simulates an optical circuit that reflects $\sim 100\%$ of the incident light, and the polarization is adjusted to maximize the power coupled into the resonator in the backward direction. Photodiodes monitor the input, transmission, and return powers of the laser, while the laser power is adjusted with a variable attenuator. Circ = fiber-optical circulator, PD = photodiode.

2. RESULTS

In our experiments, we use a fused silica microrod resonator (quality factor $Q = 1.5 \times 10^8$, diameter = 1 mm) coupled to two tapered optical fibers in an add-drop configuration [see setup in Fig. 1(b)]. Light from a diode laser at 1550 nm is sent into the microresonator in the ccw direction. The microresonator mode passively locks itself to the laser frequency, making the system insensitive to laser frequency drifts [28]. The light is then coupled out of the resonator through the second tapered fiber and directed to an optical circuit of interest. Any reflection from this circuit cannot couple back into the resonator, because it is not resonant in the cw direction, and is thus transmitted through the tapered fiber to an absorber. A common application for optical isolators is to prevent backreflections in optical circuits from disturbing the operation of a laser. One main advantage of optically induced isolation via the Kerr effect is the increase in isolation with optical power (as higher power leads to a larger frequency splitting between the cw and ccw resonator modes). We analyze the power scaling of the isolation and simulate a worst-case scenario where all of the transmitted power is reflected back to the resonator by using a fiber mirror. The behavior of the setup is characterized

with photodiodes that monitor the input, transmitted, and reflected optical power levels [see Fig. 1(b)]. Figure 2 shows the experimental results for insertion loss and isolation versus the launched optical power. The power $P_{\text{ccw}}^{\text{in}}$ corresponds to the power entering the input tapered fiber, P_{out} is the power exiting the second tapered fiber, and P_{back} is the power that passes through the resonator in the backward direction. The data in Fig. 2(a) shows an initial increase in backward-propagating light with input power. At the point where the Kerr nonreciprocity starts to split the cw and ccw resonance frequencies, the isolation kicks in and reduces the backward-propagating power, which can be seen at around 10 mW of input power in Fig. 2(a). At higher powers, the optical isolation reaches 24 dB [Fig. 2(b)]. The insertion loss of the setup (transmission in the forward direction) is around 5 dB. Note that the threshold power is comparably high as a result of the large diameter and large mode volume of the resonators in these proof-of-principle experiments. The threshold powers could be reduced significantly and the attainable isolation improved by using smaller resonators. This is illustrated in Fig. 2(c), which shows the calculated isolation in resonators made from different materials.

The theoretical curves in Fig. 2 are calculated using a model that takes into account the interaction between counterpropagating

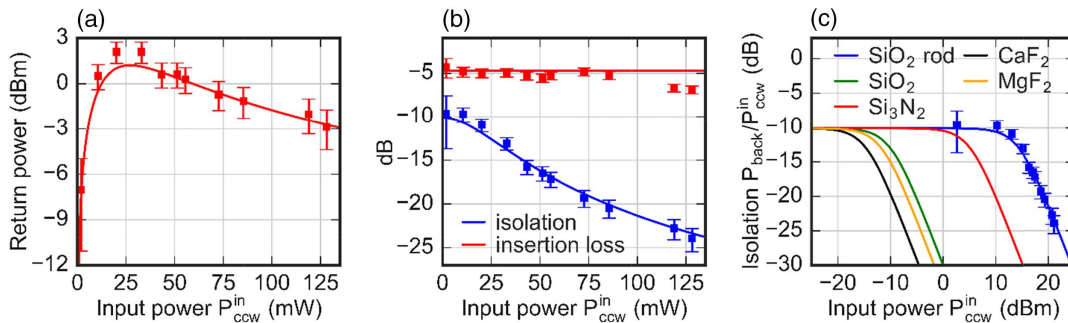


Fig. 2. Kerr-nonlinearity-induced isolation at 1550 nm, theory and experiment. (a) The measurement of the return power P_{back} versus the input power $P_{\text{ccw}}^{\text{in}}$ with a theoretical fit. For low input powers, the return power is proportional to the input power, as expected for a linear system. For high powers, the return power decreases due to the nonreciprocal Kerr effect. (b) The insertion loss $P_{\text{out}}/P_{\text{ccw}}^{\text{in}}$ and isolation $P_{\text{back}}/P_{\text{ccw}}^{\text{in}}$ versus input power. We measure an insertion loss of around 7 dB and a maximum isolation in excess of 24 dB. (c) The predicted isolation for waveguide resonators of various materials, assuming an effective mode cross-sectional area of $4 \mu\text{m}^2$ and a resonator diameter of $100 \mu\text{m}$. Our measurement (SiO₂ rod resonator, diameter 1 mm) is included for comparison. The respective Q -factors for the calculations are 10^9 for magnesium fluoride and calcium fluoride [29,30], 5×10^7 for silicon nitride [31], and 5×10^8 for SiO₂. Our calculations show isolation at sub-milliwatt power levels and even down to tens of microwatts in these currently available microresonator systems.

light via the Kerr nonlinearity. The optical powers P_{cw} and P_{ccw} coupled into the resonator in the cw and ccw directions are given by [26]

$$P_{\text{ccw}} = \frac{\eta^{\text{in}} P_{\text{ccw}}^{\text{in}}}{1 + \left(\frac{\delta}{\gamma} + \frac{1}{P_0} (P_{\text{ccw}} + 2P_{\text{cw}}) \right)^2}, \quad (1)$$

$$P_{\text{cw}} = \frac{\eta^{\text{in}} P_{\text{cw}}^{\text{in}}}{1 + \left(\frac{\delta}{\gamma} + \frac{1}{P_0} (P_{\text{cw}} + 2P_{\text{ccw}}) \right)^2}. \quad (2)$$

Here, $P_{\text{ccw}}^{\text{in}}$ and $P_{\text{cw}}^{\text{in}}$ are the powers launched in counterpropagating directions into the coupling waveguides, η^{in} is the incoupling efficiency from the waveguides to the resonator, and δ is the detuning of the laser frequency from the cold cavity resonance with a half-linewidth γ . We use a symmetrically coupled resonator, which means that $\eta^{\text{in}} = 4k(\gamma - k)/\gamma^2$ is the same for both waveguides, with k being the coupling coefficient between the resonator and each waveguide. The terms $(P_{\text{ccw}} + 2P_{\text{cw}})/P_0$ and $(P_{\text{cw}} + 2P_{\text{ccw}})/P_0$ correspond to the normalized nonreciprocal Kerr resonance frequency shifts. The factor of 2 in the dependence on the respective counterpropagating power is important for the isolator/circulator to work, which enables the isolation via interaction of counterpropagating light in a single resonator (compared to previous work on coupled microresonator systems [21]). P_0 is a resonator-specific constant given by

$$P_0 = \frac{\pi^2 n_0^2 d A_{\text{eff}} (\gamma - k)}{Q_L^2 n_2 \lambda \gamma}, \quad (3)$$

for refractive index n_0 at wavelength λ , nonlinear refractive index n_2 , resonator diameter d , effective mode area A_{eff} , and loaded quality factor Q_L . The output and return powers are given by $P_{\text{out}} = \eta^{\text{out}} P_{\text{ccw}}$ and $P_{\text{back}} = \eta^{\text{out}} P_{\text{cw}}$, with the outcoupling coefficient $\eta^{\text{out}} = k/(\gamma - k)$. Assuming that the laser is on resonance with the ccw mode, the insertion loss $P_{\text{out}}/P_{\text{ccw}}^{\text{in}}$ will be equal to the through-coupling efficiency $\eta^{\text{thru}} = \eta^{\text{in}} \eta^{\text{out}} = 4k^2/\gamma^2$. Assuming that the rest of the optical circuit has a reflectivity R such that $P_{\text{cw}}^{\text{in}} = R P_{\text{out}}$, we thus find that the isolation $I = P_{\text{back}}/P_{\text{cw}}^{\text{in}}$ is given by

$$I = \frac{\eta^{\text{thru}}}{1 + \left(\frac{P_{\text{ccw}}^{\text{in}} \eta^{\text{in}}}{P_0} (1 - IR) \right)^2}. \quad (4)$$

Note that the insertion loss of the microresonator-isolator system can be decreased by increasing the coupling to the tapered fibers. However, this would lead to a decreased Q -factor and a trade-off between the attainable isolation and insertion loss.

The resonance frequency difference in our system is on the order of 10 linewidths, corresponding to 50 MHz, and could be increased to GHz ranges by using microresonators with higher optical nonlinearity or by operating higher above the threshold power. The resonance frequency difference in terms of cavity linewidths is comparable to existing electromagnetic microresonator systems with larger absolute resonance frequency differences [32]. In terms of applications, our system could be used to isolate chip-integrated continuous-wave laser diodes (with subsequent modulation if used in telecom systems).

In addition to operating as an isolator, a microresonator in an add-drop configuration can be used to realize a three-port circulator [27], as shown in Fig. 3(a). Light sent into port 1 is transmitted via the resonator to port 2. The light circulating counterclockwise around the resonator causes the cw resonance frequency to be shifted away. This means that light of the same frequency entering port 2 cannot couple into the resonator and is instead transmitted to port 3. This was tested by splitting light from a laser between port 1 (404 mW) and port 2 (87 mW), and measuring the output powers with fast photodiodes. The transmission coefficients, i.e., the output powers normalized by the relevant input power, are plotted in Fig. 3(b) while sweeping the laser frequency across the resonance.

In our microresonator-based circulator we observe 47% transmission from port 1 to port 2 (corresponding to 3.3 dB insertion loss), and a directivity T_{23}/T_{21} of >19 dB while the microresonator is thermally locked to the laser. The oscillations in T_{23} result from interference with light from port 1 that is backscattered within the resonator. From the amplitude of these oscillations, we obtain a value of -33 dB for the (unwanted) transmission coefficient T_{13} . This is comparable with values for commercial magneto-optic circulators, and may be further improved by reducing the backscattering through surface defects of the resonator, which will also increase the Q -factor and thereby the isolation. In order to achieve stable circulation for larger laser frequency changes than those supported by the thermal self-locking of the microresonator, the resonator could be temperature controlled and/or the laser could be injection-locked to the resonance.

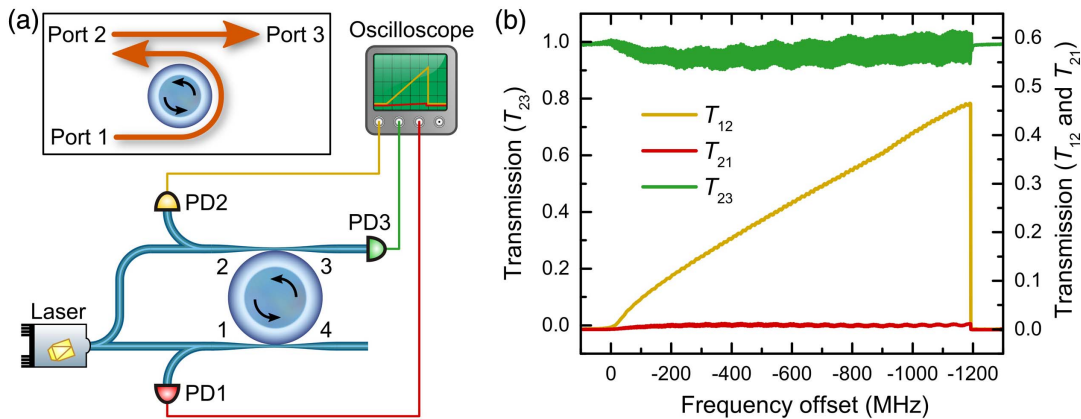


Fig. 3. Microresonator-based circulator. (a) A schematic of the setup. Light is split between ports 1 and 2, with slightly more light going into port 1, so that the resonator is set into the ccw state. Photodiodes measure the optical output power from each port. (b) The transmission T_{ij} (from port i to port j) as the laser frequency is swept through the resonance.

3. CONCLUSION

In conclusion, we have demonstrated an optical isolator and circulator based on the intrinsic nonreciprocity of the Kerr effect in an optical microresonator. The biased microresonator breaks Lorentz reciprocity and our results show increasing isolation with optical power, which is supported by the theoretical model based on the nonreciprocal $\chi^{(3)}$ -nonlinearity. In our experiments, we achieve more than 20 dB isolation. The threshold power in our millimeter-sized rod resonators is around 10 mW, which could be significantly reduced to tens of microwatts by using smaller resonators with higher finesse and higher nonlinearity. In chip-based optical devices, such isolators would be ideal for reducing back-reflections into integrated laser diodes, especially given the increasing isolation at higher optical powers. Aside from the fundamental physics of the intrinsic Kerr nonreciprocity in ring resonators, our work provides a new and simple route for realizing optical isolators and circulators for applications in integrated photonic circuits.

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[†]These authors contributed equally to this work.

See [Supplement 1](#) for supporting content.

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